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The r-process in the neutrino wind and U-Th cosmochronology

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The discovery of the highly r-process-enhanced, extremely metal-poor star, CS 31082-001 ([Fe/H] = -2.9) has provided a powerful new tool for age determination, by virtue of the detection and measurement of the radioactive species uranium and thorium. We determine the lower limit on the age of the universe by comparison of the nucleosynthesis results based on the "neutrino wind" scenario with the available spectroscopic elemental abundance data of CS 31082-001.

1. Introduction

Uranium and thorium are regarded as potentially useful cosmochronometers because their long radioactive decay half-lives (^{232}Th: 14.05 Gyr, ^{238}U: 4.468 Gyr) are significant fractions of the expected age of the universe. The excellent agreement of the relative abundances of neutron-capture elements in the extremely metal-poor ([Fe/H] = -3.1), r-process-element-enhanced star CS 22892-052 with the solar r-process pattern initially suggested that thorium might serve as a precise cosmochronometer [1]. The time that has passed since the production of the thorium that is now observed in the outer atmosphere of such an old halo star can be regarded as a hard lower limit on the age of the universe.

The second discovered r-process-enhanced, extremely metal-poor star, CS 31082-001 ([Fe/H] = -2.9) has provided a new, potentially quite powerful cosmochronometer, uranium [2]. In principle, uranium might be expected to be a more precise chronometer than thorium owing to its shorter half life. However, analysis of this star has also provided conclusive evidence that the r-process pattern is *not universal* over the actinides. Hence, any age estimates that demand assumption of the universality of the r-process pattern may in fact be unreliable. The purpose of this paper is to construct a realistic r-process model based on the neutrino-wind scenario, in order to derive initial production ratios that might be useful for estimation of the minimum age of the universe, in particular by use of the U-Th chronometer pair. The age of CS 31082-001 is derived by comparison of the nucleosynthesis results with the abundance pattern of heavy elements in this star[3].

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2. The r-process in the neutrino wind

Neutrino wind, in which the free nucleons accelerated by the intense neutrino flux near the neutrino sphere of a core-collapse supernovae assemble to heavier nuclei, has been believed to be the most promising astrophysical site of the r-process[4]. Recently, Otsuki et al. (2000) have studied the physical conditions required for the r-process in detail, using a semi-analytic model of a spherical, steady neutrino wind, taking general relativistic effects into account[5]. They suggested that robust physical conditions for the r-process were obtained only if the proto-neutron star was as massive as $\sim 2.0 M_\odot$. Furthermore, Wanajo et al. (2001) showed from nucleosynthesis calculations that the r-process yields for the compact proto-neutron star models (with a mass of $1.9 - 2.0 M_\odot$ and radius of 10 km) were in good agreement with the solar r-process pattern[6]. We use a model with a proto-neutron star with (gravitational) mass of $2.0 M_\odot$ and radius of 10 km, as in [6], whose nucleosynthesis results are in good agreement with the solar r-pattern for nuclei $A \approx 120 - 200$.

The r-process of nucleosynthesis, adopting the model described above for the physical conditions, is obtained by application of an extensive nuclear-reaction network code. The network consists of $\sim$ 3600 species, all the way from single neutrons and protons up to the fermium isotopes. We include all relevant reactions, i.e., (n,γ), (p,γ), (α,γ), (p,n), (α,p), (α,n), and their inverses[7][8]. The α-deca chains and spontaneous fission processes are taken into account only after the freezeout of all other reactions. For the latter, all nuclei with $A \geq 256$ are assumed to decay by spontaneous fission only. The few known nuclei undergoing spontaneous fission for $A < 256$ are also included, along with their branching ratios. Neutron-induced and β-delayed fissions, as well as the contribution of fission fragments to the lighter nuclei, are neglected. The electron fraction, Y_e, is varied from 0.39 to 0.49 to examine its effect on the r-process. In order to calculate the mass-integrated r-process yields, the time evolution of the neutrino luminosity, L_ν, is assumed to be $L_\nu(t) = L_{\nu 0}(t/t_0)^{-1}$. $L_{\nu 0}$ and t_0 are taken to be $10^{52.6}$ ergs s^{-1} ($\approx 4 \times 10^{52}$ ergs s^{-1}) and 0.2 s, respectively, being in reasonable agreement with the hydrodynamic results[4].

3. The U-Th cosmochronology

In Figure 1 the available spectroscopic abundance data for CS 31082-001[9] (dots) are compared with the nucleosynthesis results (thick line) and with the solar r-pattern (thin line), scaled at Eu ($Z = 63$). Nucleosynthesis results for all Y_e cases are in good agreement with the abundance pattern of CS 31082-001 for the elements between Pr ($Z = 59$) and Tm ($Z = 69$), with the exception of Tb. Note that a few of the predicted abundances for elements near the second peak (Ba, La, and Ce) are significantly deficient compared to both the observational and solar patterns. This might be due to the properties of the nuclear mass model employed in this study. The platinum-peak elements Os and Ir are in reasonable agreement, except for the $Y_e = 0.49$ case, although the height of the ^{195}Pt differs.

The age of CS 31082-001 can be inferred by application of one or more of the following three relations[9]:

$$t^*_{\mathrm{Th},r} = 46.67\,[\log(\mathrm{Th}/r)_0 - \log(\mathrm{Th}/r)_{\mathrm{now}}]\ \mathrm{Gyr} \quad (1)$$

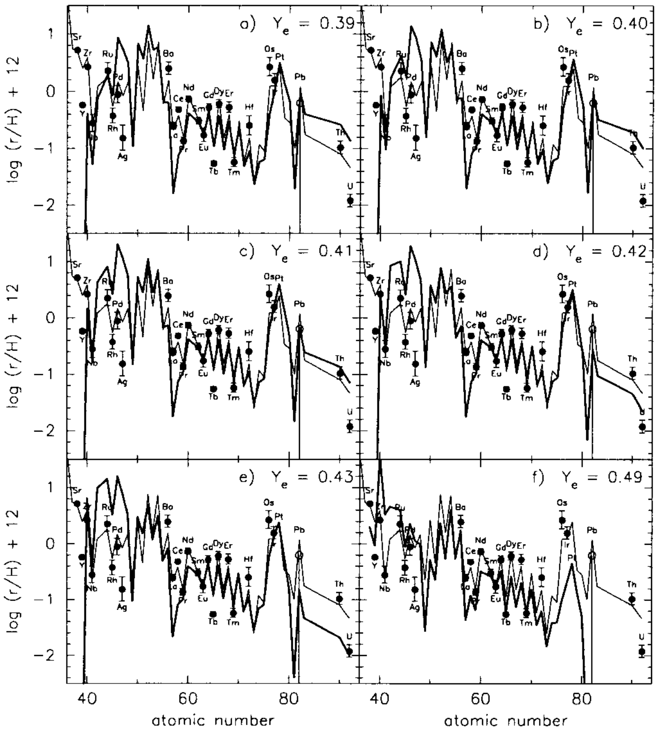

Figure 1. Comparison of the mass-integrated yields (the thick line) for Y_e = (a) 0.39, (b) 0.40, (c) 0.41, (d) 0.42, (e) 0.43, and (f) 0.49, scaled at Eu ($Z = 63$), with the abundance pattern of CS 31082-001 (filled circles, with observational error bars), as functions of atomic number. For Pb, the observed upper limit is shown by the open circle. The scaled solar r-pattern is shown by the thin line.

$$t^*_{\mathrm{U},r} = 14.84\,[\log(\mathrm{U}/r)_0 - \log(\mathrm{U}/r)_{\mathrm{now}}]\ \mathrm{Gyr} \quad (2)$$

$$t^*_{\mathrm{U,Th}} = 21.76\,[\log(\mathrm{U/Th})_0 - \log(\mathrm{U/Th})_{\mathrm{now}}]\ \mathrm{Gyr}, \quad (3)$$

where r is a stable r-element, and the subscripts "0" and "now" denote the initial and current values derived by theory and observation, respectively. With the use of these ratios as the initial values, the age of CS 31082-001 is derived as shown in in Figure 2. It is noteworthy that the age obtained from the U-Th chronometer pair is considerably more robust than the alternatives, resulting in a range $\sim 13.5 - 14.2$ Gyr, with an exception of 12.2 Gyr for the $Y_e = 0.49$ case. Therefore, we use only the U-Th chronometer for dating of this star, while the others are regarded as consistency checks only. Y_e is constrained to be ≈ 0.40, owing to the consistency between ages based on the U-Th pair and others. The difference between the ages obtained from U-Th between $Y_e = 0.39$ and 0.41 is only

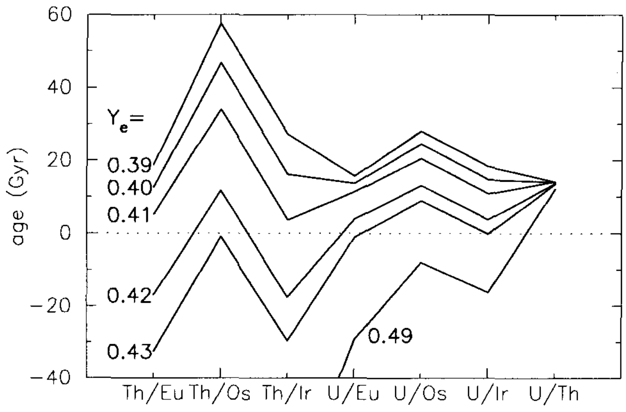

Figure 2. Ages of CS 31082-001 derived from various chronometer pairs. The robustness of the U-Th pair is clearly shown. The superiority of the U-r pairs compared to those of Th-r can also be seen.

0.1 Gyr. On the other hand, the observational error associated with the U/Th ratio, 0.11 dex, leads to an uncertainty of 2.4 Gyr from application of equation (3). We conclude, therefore, that the age of CS 31082-001 is 14.1 ± 2.5 Gyr.

It should be emphasized that the age determination made in the present paper is derived from the exploration of a single specific model based on the neutrino-wind scenario, and relies as well on the choice of one of the many existing nuclear data sets[10]. Thus, it is clear that our final result may be changed if we were to make use of other astrophysical models. Obviously, more study with other astrophysical models, as well as with a number of different nuclear data sets, are needed to derive the final results.

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